



ГОСУДАРСТВЕННЫЙ НАУЧНЫЙ ЦЕНТР РОССИЙСКОЙ ФЕДЕРАЦИИ
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ОЭФ

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Correction of the energy scale nonlinearity
in electromagnetic calorimeters with the π^0 two-photon decays

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Аннотация

М.Ю.Боголюбский и др. Коррекция нелинейности энергетической шкалы электромагнитного калориметра по двухфотонным распадам π^0 -мезона.: Препринт ИФВЭ 2010-15. – Протвино, 2010. – 6 с., 4 рис., библиогр.: 4.

В работе представлен метод вычисления коррекции нелинейности отклика электромагнитного калориметра, основанный на минимизации отклонения измеренной массы нейтрального мезона, распадающегося в конечном счете на фотоны, в зависимости энергий последних. Метод был разработан и применён для электромагнитного калориметра LGD2 в эксперименте Гиперон-М на ускорителе У70 ГНЦ ИФВЭ. Найденная коррекция позволила существенно уменьшить вариации реконструированных масс π^0 и η мезонов в зависимости от их минимальной энергии.

Abstract

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The method to calculate the non-linearity correction of the electromagnetic calorimeter response, based on minimisation of the deviation of the measured neutral meson mass on the energies of its decay photons, is described in this paper. This method was developed for the electromagnetic calorimeter LGD2 in the Hyperon-M experiment at U70 accelerator of IHEP. The found correction allowed to reduce significantly variations of the reconstructed π^0 and η masses on the minimal energy of the mesons.

Introduction

Photons and electrons due to interaction with a medium of the cell-type electromagnetic calorimeter produce electromagnetic showers which spreads over several calorimeter cells called a shower cluster, i.e. the group of affected cells with common edges. The read-out electronics for such kind of calorimeters reads the signal amplitudes from calorimeter cells. These amplitudes are used to estimate the real energy deposition of electromagnetic shower in the calorimeter cells by using the independent on energy calibration coefficients. The sum of the deposited energies in the cluster cells defines the energy of the incident photon or electron. This direct energy estimation of electromagnetic showers might be satisfactory in the energy range used for the calorimeter calibration but could lead to energy shifts at different energies which results in the calorimeter response nonlinearities caused by the physical processes, read-out electronics and shower reconstruction program.

The longitudinal electromagnetic shower profile (electromagnetic cascade in the calorimeter radiators) [1] allows to determine the shower energy deposition in the calorimeter radiators for the case of its finite longitudinal thickness. The position of the energy maximum moves further into the calorimeter with the logarithm of the photon energy, that increases the shower energy leakage out of the calorimeter. Another phenomenon of the measured shower energy loss is related to the finite attenuation length for Cherenkov or scintillation light in the calorimeter cells. The average light path from a radiation point to a photo-detector depends on the energy of the incident photon and reveals itself also as the nonlinear dependence with energy of the light pulse produced by shower. The shower energy leakage is possible in the transversal directions as well, for instance, due to energy loss in gaps between calorimeter cells.

Chosen calorimeter design could bring the nonlinearity effects as well. For instance, the used photo-detectors could have a nonlinear scale. The read-out electronics (including the analog to digit converters, ADC) could be too noisy, and the noise has to be suppressed by applying the relevant threshold on recorded amplitudes in the calorimeter cells. This threshold leads sometimes to a significant distortion of measured amplitudes of the incident photons at low energies. The enumeration could be continued. But it is important to note that all these effects are unlikely possible to take into account with a high accuracy using Monte Carlo simulations only. Anyway this is sufficiently difficult.

The typical task solving by electromagnetic calorimeters in high energy physics experiments is the mass spectra measurement of neutral mesons decaying into photons, for instance, $\pi^0 \rightarrow \gamma\gamma$, $\eta \rightarrow \gamma\gamma$, $\omega \rightarrow \pi^0\gamma$ and so on. The calorimeter energy scale nonlinearity have an impact on dependence of the measured neutral meson masses on their energies which leads, in turn, to systematic uncertainties in the meson spectra measurement. Therefore the correction of the calorimeter non-linearity response is relevant in the case.

At the same time the possibility of solving this problem directly is no means always the case, i.e. the experimental study of the calorimeter response to photons or electrons at different energies cannot be carried out, for example, at collider experiments or for other reasons. However the correction factor of energy scale of electromagnetic calorimeters could be found as the result of inverse problem solution, i.e. by using experimentally measured mass dependence of neutral mesons on the energy of decay photons.

In the present paper the mathematically strict algorithm of nonlinearity correction of the calorimeter energy scale based on the minimum squared deviation method is proposed. This algorithm has been developed and applied for the data processing from the electromagnetic calorimeter LGD2 of the experiment Hyperon-M at the U-70 accelerator of IHEP, Protvino [2]. The two photon decays of neutral pions recorded in the experiment have been used for the energy correction procedure. The performed correction allows to reduce significantly the nonlinearity of the LGD2 energy scale and to decrease systematic uncertainties in particle mass measurement in several times. It opens up the possibility to obtain the interesting physics results as well.

It is worth to note also that the events of two photon decays of neutral mesons are used for a calibration purpose of the relevant electromagnetic calorimeters in several experiments. And thus the described below procedure of the energy scale correction could be interesting for the data treatment in these experiments as well.

1. Experiment Hyperon-M

It is appropriate at first to give a short description of the Hyperon-M setup before discussing the electromagnetic calorimeter LGD2 energy scale in the experiment. The layout of experiment is presented in Fig.1. The setup comprises the beam telescope of scintillation counters S_1 , S_2 , S_4 , Cherenkov counters C_{1-3} , nuclear target T , scintillation anti counter S_A and electromagnetic Cherenkov lead glass calorimeter LGD2 located at a distance of 3.7 m after the target. The measurements were carried out on the 7 GeV/c beam of positive particles with intensity of $\sim 10^6$ particles per burst on different nuclear targets, including the Be target. The requirement of a beam particle signal from the beam telescope and the absence of a

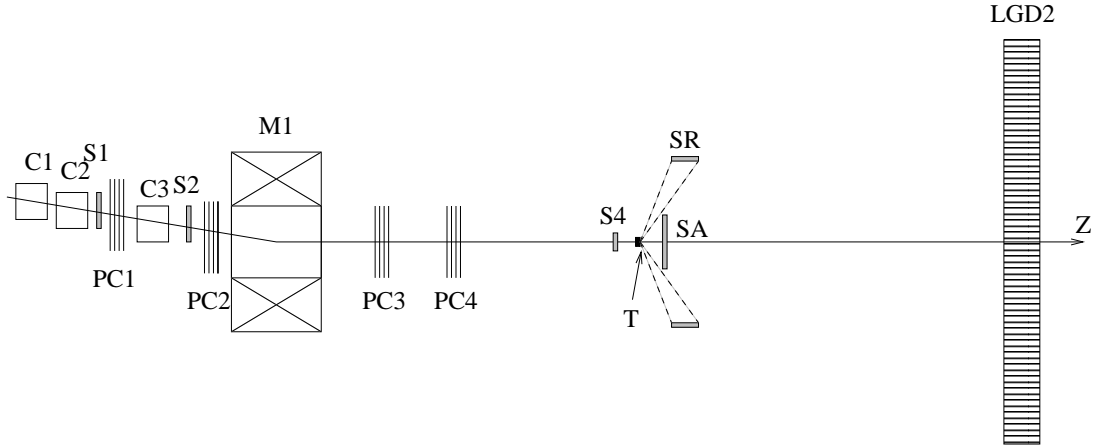


Рис. 1. The Hyperon-M experimental setup layout: S_1 , S_2 , S_4 — beam scintillation counters, C_{1-3} — Cherenkov counters, T — nuclear target, S_A — trigger scintillation anti counter S_A , PC_i — proportional chambers, LGD2 — Cherenkov electromagnetic calorimeter with lead glass radiators.

signal from anti counter S_A generates the trigger signal:

$$Tr = S_1 \cdot S_2 \cdot S_4 \cdot \bar{S}_A.$$

This trigger allows to select effectively the inclusive production of neutral mesons M^0 decaying into photons within the LGD2 calorimeter solid angle:

$$\pi^+(K^+, p) + A_z \rightarrow M^0 + X, \quad M^0 \rightarrow n\gamma. \quad (1)$$

A typical value of the trigger selectivity reached the value of $\sim 1-3 \cdot 10^{-2}$ depending on the type and thickness of the irradiated target and the beam intensity. More detailed description of the Hyperon-M setup, electronics, trigger and data acquisition system can be found elsewhere [3].

The LGD2 calibration was performed on the physics two-photon events collected on the Be target. The sample of calibration events comprises of 2 millions events (1) with the reconstructed photon multiplicity

$n = 2$ and the photon pair energy $E_{\gamma\gamma} > 1.5$ GeV. Determination of the calibration coefficients was performed by means of the iterative corrections of the π^0 -peak position with a smooth background in each calorimeter cell on the subset of two photon events where one of two photons hits this cell, details see in [4]. We note here only that the effective mass of photon pair was evaluated with the formula:

$$m_{2\gamma} = \sqrt{2\varepsilon_1\varepsilon_2(1 - \cos\theta_{12})}, \quad (2)$$

where ε_i is the measured energy of the i -th photon and θ_{12} is the opening angle of photon pair in the laboratory frame. The effective mass spectrum of photon pairs in reaction (1) after 15 iterations is illustrated by Fig. 2. The obtained mass resolution for the π^0 -meson is equal to 11.4 MeV.

2. The calorimeter energy scale correction procedure

Let's define the nonlinear correction to the calorimeter LGD2 energy scale $\Delta\varepsilon$ as the difference between the "true" photon energy $\tilde{\varepsilon}$ and its measured value ε :

$$\Delta\varepsilon = \tilde{\varepsilon} - \varepsilon. \quad (3)$$

This correction can be expanded in a power series over some variable x depending on the photon energy

$$\Delta\varepsilon = \sum_{i=0}^{i=k} \alpha_i \cdot x^i \quad (4)$$

taking into account that the correction $\Delta\varepsilon$ should be comparatively small with respect to the measured photon energy. To avoid the computational precision limitations at large energy values related to the factorisation order k in expression (4), it is natural to take for the x variable the logarithm of measured photon energy:

$$x = x(\varepsilon) = \ln(\varepsilon/\varepsilon_0), \quad (5)$$

where $\varepsilon_0 = 1$ MeV. As a consequence the corrected photon energy $\tilde{\varepsilon}$ can be written as:

$$\tilde{\varepsilon}(\varepsilon) = \varepsilon + \Delta\varepsilon = \varepsilon \left(1 + \sum_{i=0}^{i=k} \frac{\alpha_i}{\varepsilon} x^i\right), \quad (6)$$

where it is natural to assume that the parameters α_i/ε are sufficiently small due to a small nonlinearity of the calorimeter energy scale. The expression for the effective mass of a photon pair (2) can be rewritten then in terms of the corrected energies of photons as follows:

$$\tilde{m}_{2\gamma} = \sqrt{2\tilde{\varepsilon}_1\tilde{\varepsilon}_2(1 - \cos\theta_{12})} = \sqrt{\tilde{\varepsilon}_1\tilde{\varepsilon}_2} \cdot c_{12}, \quad (7)$$

where $\tilde{\varepsilon}_i = \tilde{\varepsilon}(\varepsilon_i)$ are linear functions (6) of small parameters α_i/ε and $c_{12} = \sqrt{1 - \cos\theta_{12}}$ is the geometrical factor which is actually independent on these parameters.

The parameters α_i in equation (6) can be determined by minimisation of the deviation of effective mass of the photon pair in representation (7) from the PDG π^0 -meson mass on the sample of π^0 events used in the discussed procedure and shown for our case in Fig.2 (left) as hatched area. In other words, the parameters α_i can be determined by means of the functional minimisation

$$\chi^2 = \sum_{n=1}^N \frac{(\tilde{m}_{2\gamma} - m_{\pi^0})^2}{\sigma^2(m_{2\gamma})}, \quad (8)$$

where N is the number of two-photon events in the indicated π^0 -peak region in Fig.2, $\tilde{m}_{2\gamma}$ is the effective mass of a photon pair in the representation (7), m_{π^0} is the PDG value of the π^0 -meson mass and $\sigma(m_{2\gamma})$ is the expected uncertainty of the effective pair mass as defined in expression (2).

The uncertainties on the invariant mass of photon pair include the photon energy uncertainty and the uncertainty of the photon pair opening angle, see (2). The opening angle error is defined by the Hyperon-M setup geometry and the reconstruction program of LGD2 calorimeter. This error is sufficiently small in our case, and we will neglect it below.

The relative uncertainty of the photon energy measurement in electromagnetic calorimeter is defined according to the formula:

$$\sigma_\varepsilon/\varepsilon = a/\sqrt{\varepsilon} \oplus b \oplus c/\varepsilon,$$

where parameters a , b and c are defined by the calorimeter design, see for example [1]. The last summand contribution in the energy resolution of LGD2 calorimeter is small and we will ignore it below. Thus the expected mass resolution for photon pairs can be express using the error propagation techniques as:

$$\sigma^2(m_{2\gamma}) = A(c_{12}^2(\varepsilon_1 + \varepsilon_2) + B), \quad (9)$$

where the energies of photons are measured in GeV, and A and B are the empirical parameters equal to $2.5 \cdot 10^{-3}$ GeV and $1.4 \cdot 10^{-3}$ GeV respectively for the LGD2 spectrometer.

The necessary conditions for functional (8) minimisation

$$\partial\chi^2/\partial\alpha_i = 0$$

with the accuracy up to the second order smallness $\alpha_i\alpha_j/\varepsilon^2$ result in the system of linear equations relatively to the parameters α_j :

$$\begin{aligned} \sum_{j=0}^k \alpha_j \sum_{n=1}^N \frac{c_{12}^2}{2\varepsilon_1\varepsilon_2\sigma^2(m_{2\gamma})} (\varepsilon_1x_2^i + \varepsilon_2x_1^i)(\varepsilon_1x_2^j + \varepsilon_2x_1^j) = \\ = \sum_{n=1}^N \left(\frac{m_\pi^0}{\sqrt{\varepsilon_1\varepsilon_2}} - c_{12} \right) \frac{c_{12}}{\sigma^2(m_{2\gamma})} (\varepsilon_1x_2^i + \varepsilon_2x_1^i), \end{aligned} \quad (10)$$

where $x_l = x(\varepsilon_l)$, $l = 1, 2$, see equation (6). The iteration procedure based on equations (6) and (10),

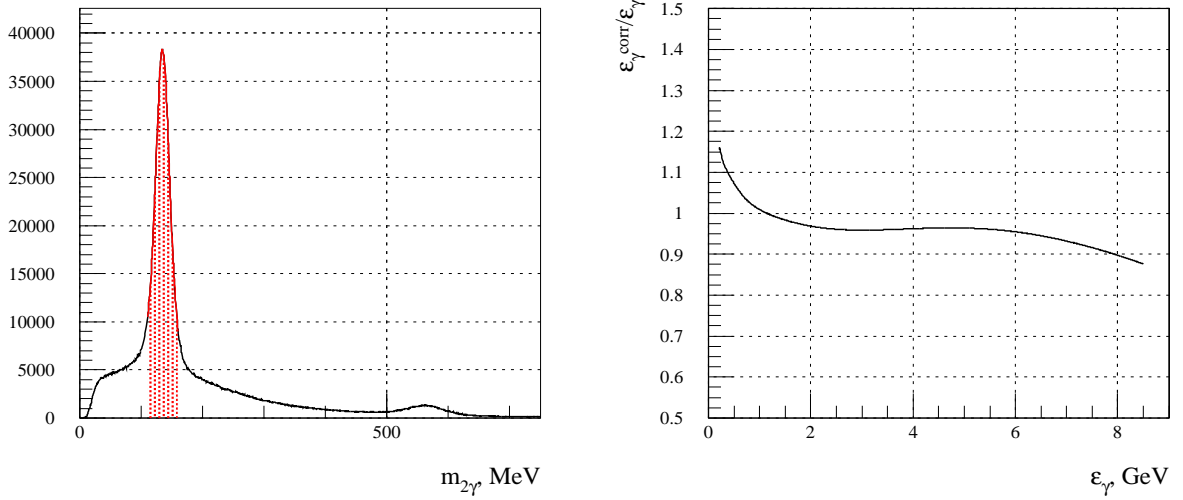


Рис. 2. Left: the effective mass spectrum of two-photon events with the sum energy of photons larger than 1.5 GeV. Right: the energy scale correction function for LGD2 calorimeter defined on the π^0 event sample and shown as hatched area in picture on left.

allows one to find out the functional minimum (8) with a reasonably good accuracy after 2 – 3 iterations.

The first 9 terms of the series (6), i.e up to the order of $k = 8$, were taken into account for the Hyperon-M data treatment. The next values for the correction coefficients have been obtained after the first iteration: $\alpha_{0-8}/GeV = 0.00399, -0.0505, -0.0392, -0.0209, -0.00537, 0.0165, 0.0104, -0.00313, -0.00235$. The coefficients of the second iteration were found to be about three times less compared with the first iteration values. The energy correction function for the LGD2 calorimeter

$$\varepsilon^{corr}/\varepsilon = \tilde{\varepsilon}(\varepsilon)/\varepsilon = 1 + \sum_{i=0}^{i=k} \frac{\alpha_i}{\varepsilon} x^i \quad (11)$$

is presented in Fig.2 in the right plot. As one can see from the figure the relative correction doesn't exceed 10% level virtually in the whole energy range of photons and this is in a good agreement with our initial assumption concerning the smallness of an expected energy scale nonlinearity of the LGD2 calorimeter. This is an important statement because it is used in the ground of the method. For the sake of completeness it would be useful also to present the values of χ^2 (8) before and after the correction: in our case the value of χ^2 per degree of freedom before the correction and after it are equal to 1.073 and 1.044 respectively for approximately 10^6 degrees of freedom.

3. Results and discussion

Performance of the above discussed procedure is illustrated in Fig.3, where the scatter plots of the effective two photon mass versus the logarithm of the energy of each photon in a pair (two points per event) for the reconstructed two-photon events (1) is shown for *Be*-target before the energy scale correction on the left panel and after it on the right panel of the figure. A clear correlation of the two-photon mass and the photon energies for events in the π^0 -meson region is seen on the left picture and it is completely absent on the right one. The numerical values of the correlation coefficients for events without the energy scale correction and with it are equal to 0.13 and 0.05 respectively.

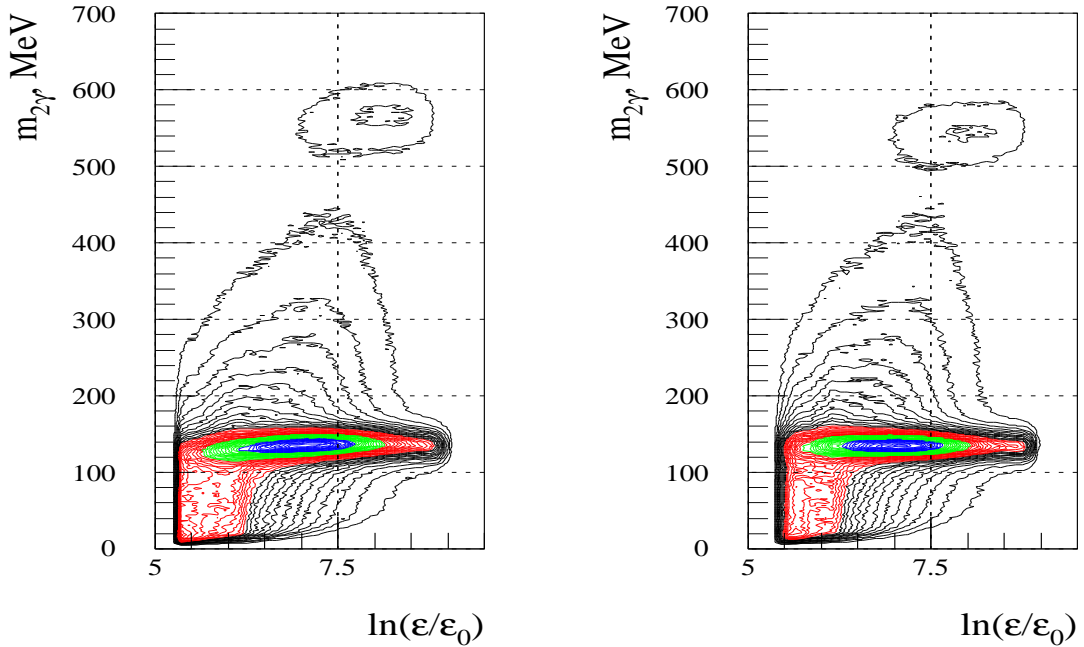


Рис. 3. Distributions of the two-photon effective mass versus the logarithm of photon energy of each photon in pair (two points per event) for the reconstructed two-photon events on *Be*-target. The concentration of events at lower area corresponds to the detection of π^0 -mesons, upper one – to the η -mesons. The event distributions before the energy scale correction are shown on left and after the correction – on right.

Another illustration of the nonlinearity correction method is represented by Fig. 4. The dependence of the measured mass of the π^0 - and η -mesons on the minimal photon pair energy ($\varepsilon_{\text{sum}} = \varepsilon_1 + \varepsilon_2$) is shown before applying the nonlinearity correction and after it. These plots demonstrate as well that the systematic deviation of the neutral pion mass from the PDG value in dependence on the photon pair energy decreases from 1.17% to 0.19%, i.e. in 6 times, and the same deviation for η -meson decreases from 2.98% to 0.23%, i.e. in 13 times, and this is demonstration of the high performance of the proposed method as a whole.

Conclusion

This paper describes the procedure of the energy scale correction for electromagnetic calorimeters. The procedure is based on the minimization of mass resolution for two-photon decays of neutral pion

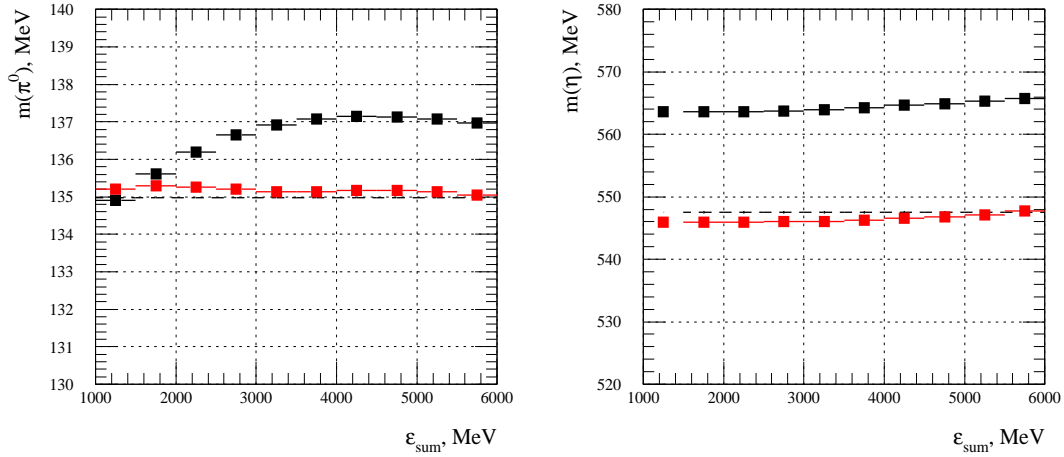


Рис. 4. The mass dependence of π^0 -meson (on left) and η -meson (on right) versus the minimal photon pair energy $\varepsilon_{\text{sum}} = \varepsilon_1 + \varepsilon_2$. The dependence before the LGD2 energy scale correction is shown by black colour and one after correction is shown by red colour. The dashed line shows the PDG values of these mesons.

detected in the calorimeter. The linear parametrisation of the correction function as the power series in logarithm of the photon energy allows to provide a simple and effective energy scale correction in a very wide energy range. Possibility to use the physics statistics of the experiment for the energy correction procedure results in the high accuracy and sensitivity of the method. For instance, in the Hyperon-M experiment the reached mass scale nonlinearity for two-photon events is equal to 0.2%, that hardly can be obtained in calculations of similar corrections by Monte-Carlo methods due to restrictions peculiar to the transport code. Anyway the significant Monte-Carlo difficulties appear in calculations at the accuracy level of 10^{-3} .

Eventually, it is significant that the described procedure could be applied practically for any hodoscopic electromagnetic calorimeter if the physics statistics of experiment possesses the needed amount of two-photon or, let's say, three-photon decays of known mesons because this procedure could be easily generalised for multi-photon decays as well.

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